

**IMPROVING TRAVEL TIMES FOR EMERGENCY
RESPONSE VEHICLES: TRAFFIC CONTROL
STRATEGIES BASED ON CONNECTED VEHICLES
TECHNOLOGIES**

Final Report



TranLIVE

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September 2014

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1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Improving Travel Times for Emergency Response Vehicles: Traffic Control Strategies Based on Connected Vehicles Technologies		5. Report Date September 2014	
		6. Performing Organization Code KLK900-SB-001	
7. Author(s) Jordan, Craig; Cetin, Mecit		8. Performing Organization Report No. N14-15	
9. Performing Organization Name and Address Old Dominion University 4111 Monarch Way, Suite 204 Norfolk, VA 23506 Source Organization Name and Address TranLIVE/NIATT University of Idaho 875 Perimeter Dr. MS0901 Moscow, ID 83844-0901		10. Work Unit No. (TRAIS)	
		11. Contract or Grant No. DTRT12GUTC17	
12. Sponsoring Agency Name and Address US Department of Transportation Research and Special Programs Administration 400 7th Street SW Washington, DC 20509-0001		13. Type of Report and Period Covered Final Report: August 2012– September 2014	
		14. Sponsoring Agency Code USDOT/RSPA/DIR-1	
15. Supplementary Notes:			
16. Abstract This research is focused on developing and evaluating new traffic control strategies to enable emergency response vehicles (EVs) to travel in transportation networks as quickly as possible while the disruption to the rest of the traffic is kept to a minimum. Providing the best possible route or trajectory for an EV depends on the traffic conditions, the type of roadway, and other relevant factors. For instance, under light traffic on multilane highways, vehicles equipped with Vehicle-to-Vehicle (V2V) communications can be alerted to clear a particular lane to allow the EV to pass by at its desired speed. If the lanes are wide enough or there is a wide shoulder, vehicles can also be directed to move to the shoulder to provide the EV an unobstructed path. However, under congested conditions on roadways with narrow lanes, enabling the EV to traverse the road at high speeds may not be trivial since there is no obvious solution to clear a lane for the EV. In this research, new methods and traffic control strategies are developed to optimize the travel time of an EV in a transportation network with signalized intersections. It will be assumed that regular vehicles have communications capabilities and comply with the alert messages sent by the EV. The proposed strategies are evaluated in microscopic simulation software (e.g., VISSIM).			
17. Key Words Vehicle-to-infrastructure communication, shock wave theory, signal preemption, microscopic simulation and emergency response vehicles		18. Distribution Statement Unrestricted; Document is available to the public through the National Technical Information Service; Springfield, VT.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 38	22. Price ...

TABLE OF CONTENTS

FIGURES	ii
TABLES	ii
EXECUTIVE SUMMARY	1
INTRODUCTION	2
BACKGROUND / LITERATURE REVIEW	4
STRATEGY FORMULATIONS	7
Platoon Split Strategy	7
Clearing Path for the EV for One Intersection.....	8
Clearing Path for the EV for Two Intersections	10
Emergency Vehicle Preemption Strategies.....	13
Queue Length Based Preemption Order	14
Sequential Preemption Based on Queue Lengths	20
All-At-Once	21
SIMULATION.....	22
Platoon Split Strategy	22
Simulation Scenarios	22
Signal Preemption Strategy.....	23
Assumptions/Limitations	24
RESULTS	25
Platoon Split Strategy	25
Theoretical Results.....	25
Simulation Results	26
Market Penetration Effectiveness	30
Signal Preemption Strategy.....	31
CONCLUSIONS.....	34
ACKNOWLEDGEMENTS	35
REFERENCES	36
APPENDIX.....	38

FIGURES

Figure 1: Shock wave profile for a single queue at a traffic light and the trajectories of the EV and preceding vehicle. 7

Figure 2: Shock wave diagram for boundary condition Q_L 12

Figure 3: Typical shock wave diagram at adjacent intersections. 16

Figure 4: Shock wave diagram for signal preemption timing..... 20

Figure 5: Percent improvement in EV travel time for one intersection at varying speed settings. 27

Figure 6: Percent improvement in EV travel time at varying intersection spacing and varying speed settings. 29

Figure 7: Percent travel time savings for different market penetration rates..... 31

TABLES

Table 1: Traffic Signal Preemption Timing..... 18

Table 2: Theoretical Time Savings 26

Table 3: Confidence Intervals for Average EV Travel Time Difference 30

Table 4: Confidence Intervals for Average EV Travel Time Difference 32

Table 5 Average Background Traffic Delay for Minor Approaches 33

EXECUTIVE SUMMARY

This research evaluated and tested routing strategies for emergency vehicles (EV) to reduce response times and for improving EV location awareness to background traffic. It was directed at developing strategies using connected-vehicles and connected-infrastructure to exchange locations, speeds, and signal timings to allow EVs to travel efficiently and safely through urban environments.

Two concepts were evaluated in this study. The first involved navigating EVs through congestion by sending maneuvering information to background traffic to allow the EV to proceed through congested signalized intersections as quickly as possible. This was achieved by creating a split in the vehicle queue in one lane at a critical location to allow the EV to proceed at its desired speed while minimizing the disruption to the rest of the traffic. The proposed method used kinematic wave theory (i.e., shock wave theory) to determine the critical point in the vehicle queue. The proposed method was simulated in a microscopic traffic simulator for evaluation. The results showed that this strategy can shorten the travel time significantly for EVs through congested signalized intersections. The research findings were presented at the 2013 Transportation Research Board Annual Conference and subsequently published in the Transportation Research Record.

The second involved a strategy of evaluating the order of traffic signal preemption. This strategy used shockwave theory to determine the order in which a group of signalized intersections should be preempted based on the vehicle queues on the EV's approach leg. This allowed for vehicle queues at downstream intersections to be discharged prior to the arrival of upstream vehicle platoon. After the EV passed each intersection, the traffic signal reverted back to normal operation. The proposed method was simulated in a microscopic traffic simulator for evaluation. The results showed that this strategy can shorten the travel time for EVs through closely spaced signalized intersections. The research findings have been submitted to the 2015 Transportation Research Board Annual Conference.

INTRODUCTION

Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications are being used to develop new applications to improve system operations and safety. By sharing vehicle information such as speed and location between vehicles and the infrastructure, a more efficient transportation network can be created. Some areas of active research include improving on-ramp merging at freeways (1), cooperative driving (2; 3), intelligent and safer signal timing design and control (4; 5), queue length estimation (6; 7) and travel time estimation across transportation networks to develop real time route guidance and traveler information systems (8-10). The application of these systems has the potential to provide travelers with detailed information on the status of the transportation network.

An area that has seen an increase in research pertains to emergency response vehicles (EVs, including police vehicles, ambulances, and fire trucks). Equipping an EV with a V2V/V2I communication system could improve response times (11) by transmitting the location, route, and final destination to vehicles and infrastructure in its path. ERITCO, an intelligent transportation system firm in Europe, has developed the Rescue system (<http://www.ertico.com/assets/download/GST/RESCUE.pdf>), which allows vehicles to be outfitted with a communication device and visual display to alert drivers of the approach of an EV. The system also allows the transmission of data between equipped non-emergency vehicles to alert drivers of the location of the EV at the emergency scene.

Providing the best possible route for an EV depends on the geometric features of the roadway network as well as the traffic conditions. Under light traffic on multilane highways with wide lanes or shoulders, vehicles can be alerted of the approach of an EV and clear a particular lane to allow the EV to pass unobstructed. However, on narrow roadways under congested conditions, there is no obvious solution to allow an EV to travel at its desired speed through the intersection.

This report evaluates two strategies to allow EVs to travel through signalized intersections on congested roadway segments. The first strategy is designed to address EVs in vehicle queues on two-lane divided roadways without shoulders at traffic signals. It involves stopping traffic on one lane at a critical point to allow the EV to change lanes so that it can travel unimpeded through the intersection. The objective is to manage the queued traffic such that the EV clears the

intersection safely and as quickly as possible while minimizing the impacts on other traffic. The second strategy is designed to assist EVs before they reach congested signalized intersections by preempting the downstream traffic signals a specific order that will allow downstream vehicle queues to discharge prior to the arrival of an EV.

The evaluation of both strategies was performed in a microscopic traffic simulator, which provides flexibility in testing environments and duplication of traffic patterns for strategy comparison. The information exchange between vehicles was not explicitly modeled. It was assumed that all vehicles can receive the messages sent by the EV and comply with the given instruction.

The strategies make use of the Lighthill-Whitham-Richards (LWR) model (12) which is a linear model used to describe traffic flow dynamics and is well suited for predicting shock waves. It arises from the conservation of vehicles principle and a fundamental diagram that relates flow to density.

This study demonstrates how the LWR model can be utilized to make predictions about the evolution of the traffic over time and space and how such information can be used to improve EV travel times under congested conditions.

BACKGROUND / LITERATURE REVIEW

EVs are painted with specific colors and are equipped with audible and visual devices for identification and to alert other vehicles of its relative position. The devices and markings communicate to drivers that an EV is near, prompting them to respond according to state guidelines. Communication effectiveness is limited by background and in-vehicle noise and is dependent on whether vehicles are within visual and audible range. Drivers can have difficulty identifying the specific location of the source and the path of the EV (13).

In addition to acknowledging the presence of an EV, drivers need to know where the EV is and how to react appropriately to its approach. State guidelines instruct drivers to change lanes to the right, if applicable, and to stop when an EV approaches from behind. Drivers must know the location of the EV, the direction the EV is going, and what they should do to allow the EV to pass safely. The lack of understanding on where to go or where the EV is located has been identified as a cause of EV crashes. Auerbach et al. (14) reported that drivers who were involved in a collision with an ambulance frequently stated that they were unaware of the ambulances' presence. A separate study on ambulance crash data reported that in 2009, the U.S. had a total of 1,404 ambulance crashes while using lights and sirens. The report was based on data from the Fatality Analysis Reporting System (FARS), the National Highway Traffic Safety Administration (NHTSA), and the National Automotive Sampling System (NASS) General Estimates System (GES) (15).

In the majority of collisions that involve an EV, the EV does not continue on the emergency call (16). Another EV needs to be dispatched to the original call, resulting in a significant delay before aid can be provided. Auerbach et al. (14) reported that when an ambulance is involved in a collision, an average delay of 9.4 minutes results before the original patient reaches the hospital. In addition to the response delay, an EV often needs to be dispatched to the collision location involving the original EV.

A United Kingdom study indicated that a reduction in response time to people in need of emergency cardiac care has the potential to increase survival rate of the patient (17). The study indicated that a reduction in response times to cardiac patients from 14 minutes to 8 minutes

could increase the percentage of survivors from 6% to 8% and a reduction to 5 minutes could increase the percentage of survivors to between 10% and 11%.

The American Heart Association also emphasizes the importance of early response. They report that for each minute between the time of a cardiac arrest to the time a defibrillator is used, the survival rate reduces by between 7% to 10% (18).

Studies that have been performed on EVs have not specifically addressed strategies to aid EVs through signalized intersections. Moussa (19) developed a lane changing strategy that focused on the evacuation of EVs on highways. The strategy involves creating gaps between vehicles on a two-lane roadway by sending messages that instruct Non-EVs to change lanes to the higher density lane.

Toy et al. (20) used unique strategies to assist EVs in traveling to destinations on highways through congestion. They evaluated the manipulation of vehicles on an automated highway to aid in the advancement of an EV as quickly as possible. The strategies involved the grouping of vehicles into platoons and shifting them left, right, forward, and backward to form gaps on the congested highway segment to allow the EV to pass.

Yoo et al. (21) developed a strategy to reduce response times by reserving lanes on roadway segments along an EV's route. Non-EVs are instructed to move out of the reserved lane to provide a path for the EV. The study introduced a short range (when the EV encounters vehicles) and a long range implementation (over the entire EV route) to assist in response time.

Other methods used to reduce the travel time of EVs are with signal preemption. Signal preemption is designed to provide a green light for approaching EVs while stopping traffic on all other intersection approaches. By stopping specific traffic movements, background vehicles no longer conflict with the approaching EV which reduces the risk of collision. In addition, the provision of a green light for an approaching EV allows queued traffic in the EV's path to clear prior to its arrival. The system works through a one-way communication system between the EV and traffic signals. EVs equipped with emitters communicate its approach by the use of light, sound, or radio waves (depending on the system) to a detector at the traffic signal. The detector receives the message and adjusts the signal timing. Recent advancement in signal preemption

technology has incorporated GPS systems to determine EV's speed and heading. Although the system provides enhancements to existing preemption technology, it lacks the ability to assess traffic congestion at downstream intersections.

There have been studies on improving the EV travel time and addressing strategies to aid EVs through signalized intersections. A number of studies have been performed to address signalized intersections through the use of signal preemption at intersections (22-24).

STRATEGY FORMULATIONS

The following sections provide descriptions on the formulation of the two strategies identified in the previous section.

Platoon Split Strategy

As a traffic light alternates between green and red phases it creates discontinuities or shock waves in the traffic stream. The LWR theory is particularly suitable to predict these shock waves since the boundary conditions are well-defined (e.g., the backward moving shock waves start at the stop bar when signal phase changes). Furthermore, the queue discharging process at signalized intersections has been shown to be quite stable (25), which enables predicting the shock wave speed reliably.

Figure 1 shows a typical shock wave diagram for the formation and dissipation of a queue at a traffic light. The backward moving shock waves start at t_R (the beginning of the red phase) and t_0 (the time when the EV joins the back of the queue and the traffic signal turns green) and thus represent the back of the queue and front of the queue (or discharging process), respectively. The speed of the shock wave for the queue discharge, w , and the free-flow speeds (or desired speeds) of regular vehicles and EV are assumed to be known.

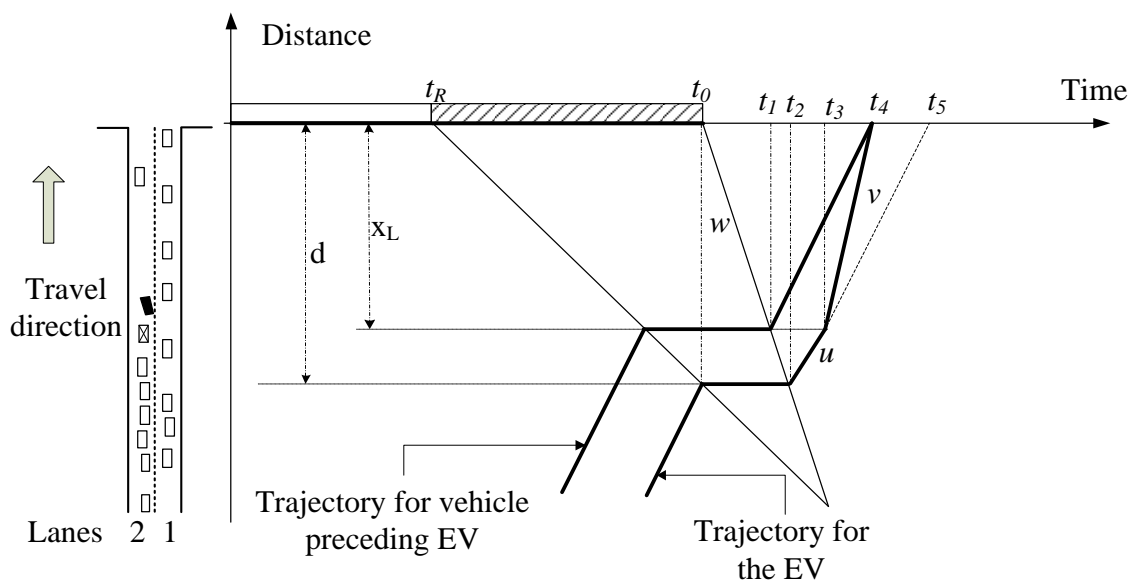


Figure 1: Shock wave profile for a single queue at a traffic light and the trajectories of the EV and preceding vehicle.

Clearing Path for the EV for One Intersection

This strategy involves clearing a path for an EV through one signalized intersection on a two-lane congested roadway facility as quickly as possible while having minimal impact to background traffic. The EV is in a vehicle queue waiting for the signalized intersection to turn green and receives a call to travel to an arbitrary point downstream of the intersection.

The solution to this problem was developed using shock wave analysis and involves stopping vehicles in the adjacent lane to clear a path for the EV to change lanes and travel unimpeded through the signalized intersection. Figure 1 provides a shock wave profile of this strategy. The EV is represented by the black vehicle on the left side of the figure and initially starts in lane 1. Its trajectory is represented by the thick black line. At time t_0 , the EV receives a call instructing it to proceed to a destination downstream of the signalized intersection.

Immediately after the received call, the EV sends a message to the traffic signal to turn green and to the vehicle located at distance x_L from the stop bar to hold its position (vehicle denoted with an “X” in Figure 1). At time t_1 , the departure shock wave reaches the vehicle preceding the stopped vehicle. The preceding vehicle departs and a gap forms between it and the stopped vehicle. At time t_2 , the departure shock wave reaches the EV, which allows it to proceed forward but with an initial velocity of u (the desired speed of the background traffic). When the EV passes the stopped vehicle located at x_L from the stop bar (time t_3), the EV changes lanes and travels at a velocity of v (the desired speed of the EV) through the intersection. The trajectories of the EV and the vehicle preceding the stopped vehicle meet at time t_4 . Assuming that the location of the EV in the vehicle queue and the velocities of the EV and the background vehicles are known, a formulation can be developed based on the shock waves to determine the critical location to stop a vehicle in the adjacent lane for a short duration to make way for the EV. The formulation is described below and the following variables are used in the formulation:

- w : the shock wave speed for the discharging flow at the signalized intersection
- v : desired speed of the EV
- u : desired speed for background vehicles
- x_L : the critical distance from the intersection to the point where queue needs to be split
- d : distance from the EV (when in the queue) to the intersection

Assuming t_0 (the time when the EV receives the message) is zero, the time at which the vehicle preceding the stopped vehicle departs the queue can be found by dividing the distance x_L by the shock wave departure speed w . The equation is as follows:

$$t_1 = \frac{x_L}{w} \quad (1)$$

The departure time for the EV from the queue (time t_2) can also be found by dividing its distance from the intersection (d) by the shock wave speed w .

$$t_2 = \frac{d}{w} \quad (2)$$

The time when the EV changes lanes at point x_L (time t_3) and begins traveling at its desired speed can be found by dividing the distance between the EV and the stopped vehicle by the initial speed u and adding it to time t_2 .

$$t_3 = t_2 + \frac{d - x_L}{u} = \frac{d}{w} + \frac{d - x_L}{u} \quad (3)$$

After the EV changes lanes, it travels to the intersection reaching it at the same time as the preceding vehicle (time t_4). The time can be calculated for both the EV and the preceding vehicle with two equations. For the preceding vehicle, the equation is

$$t_4 = t_1 + \frac{x_L}{u} = \frac{x_L}{w} + \frac{x_L}{u} \quad (4)$$

For the EV, the equation is

$$t_4 = t_3 + \frac{x_L}{v} = \frac{d}{w} + \frac{d - x_L}{u} + \frac{x_L}{v} \quad (5)$$

Solving (4) and (5) simultaneously for x_L results in the following relationship:

$$x_L = d \frac{w^{-1} + u^{-1}}{w^{-1} + 2u^{-1} - v^{-1}} \quad (6)$$

If the queue on lane 2 is split at location x_L , the EV will be able to travel over distance x_L at its desired speed v . This will result in a theoretical time saving that is equal to the difference $t_5 - t_4$.

Clearing Path for the EV for Two Intersections

In this scenario, the destination of the EV is located at a point beyond two intersections. The shock wave corresponding to this scenario is shown in Figure 2. Similar to Figure 1, the trajectories of the EV and the preceding vehicle are shown. The idea is to find the critical point to stop traffic in the adjacent lane so the EV can change lanes to travel at its desired speed (v) through the upstream intersection and travel unimpeded through the downstream intersection. For this scenario to be successful, traffic signal preemption needs to occur at the upstream and downstream intersections.

To formulate the critical point to split the platoon, limiting assumptions needed to be made. The downstream vehicle queue is assumed to be moving prior to the first vehicle in the upstream platoon reaching the back of the queue. In addition, no traffic from access points other than the first intersection is considered. The speeds of the discharging shock wave from the upstream and downstream intersections are assumed to be equal. Additionally, it is assumed that there is sufficient storage downstream of the intersections to accept the discharging vehicles.

The formulation for calculating the critical point to split the platoon is similar to the previous scenario with the inclusion of a new variable z (the distance between intersections). The formulation for the timing of the preemption is provided after the platoon split formulation.

Assuming t_0 is zero, the departure time from the queue for the preceding vehicle can be found as follows:

$$t_1 = \frac{x_L}{w} \quad (7)$$

The departure time from the queue for the EV is

$$t_2 = \frac{d}{w} \quad (8)$$

The time when the EV changes lanes and starts traveling at its desired speed can be found as:

$$t_3 = t_2 + \frac{d - x_L}{u} = \frac{d}{w} + \frac{d - x_L}{u} \quad (9)$$

The time at which the preceding vehicle and the EV reach the downstream intersection at the same time t_4 is calculated with the following two equations, respectively:

$$t_4 = t_1 + \frac{x_L + z}{u} = \frac{x_L}{w} + \frac{x_L + z}{u} \quad (10)$$

$$t_4 = t_3 + \frac{x_L + z}{v} = \frac{d}{w} + \frac{d - x_L}{u} + \frac{x_L + z}{v} \quad (11)$$

Solving (10) and (11) simultaneously for x_L provides the following equation:

$$x_L = \frac{d(w^{-1} + u^{-1}) + z(v^{-1} - u^{-1})}{(w^{-1} + 2u^{-1} - v^{-1})} \quad (12)$$

If the queue on lane 2 is split at location x_L , the EV will be able to travel over the distance $x_L + z$ at its desired speed (v). This will result in time savings that equals the difference $t_5 - t_4$.

To clear potential vehicle queues at the downstream intersection, a formulation was developed by using the LWR method to specify the time at which the downstream intersection turns green in reference to when the EV enters the back of the queue (time t_0). Figure 2 shows the shock waves that define the boundaries of the queue and the trajectory of the EV. The formulation for calculating this critical time is provided below and uses a new variable Q_L (the length of the queue at the downstream intersection).

The time the first vehicle departing from the upstream intersection reaches the back of the queue at the downstream intersection can be found as,

$$t_6 = \frac{z - Q_L}{u} \quad (13)$$

The time it takes for the vehicle queue at the downstream intersection to discharge can be calculated with,

$$t_6 = t_G + \frac{Q_L}{w} \quad (14)$$

where t_G is the time the signal turns green.

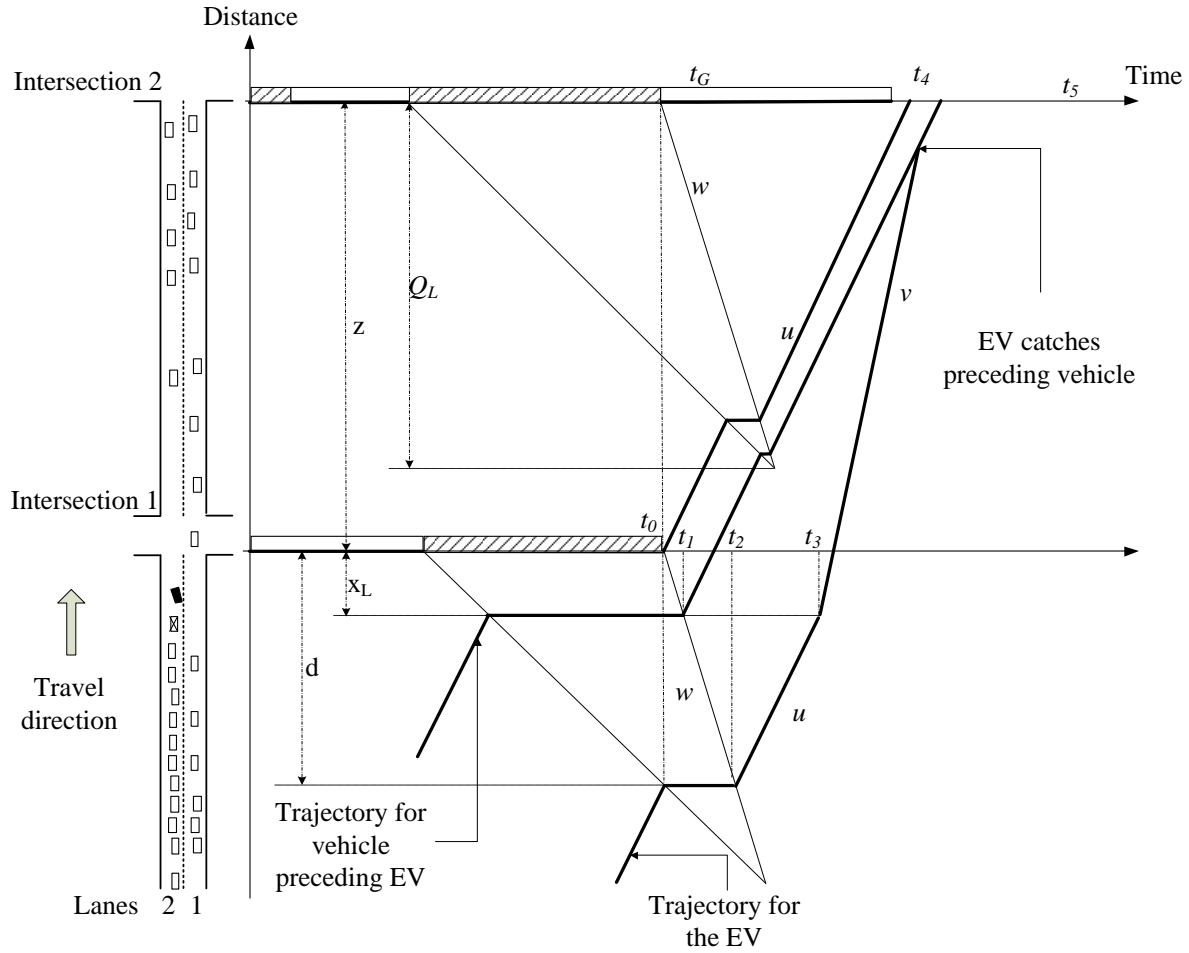


Figure 2: Shock wave diagram for boundary condition Q_L .

Solving (13) and (14) simultaneously for t_G provides the following equation:

$$t_G = \frac{z - Q_L}{u} - \frac{Q_L}{w} \tag{15}$$

Time t_G is relative to time t_0 and therefore the downstream intersection should turn green t_G seconds after time t_0 .

The formulation developed in this study assumes a simplified transportation system between two intersections and provides a straightforward solution for the platoon split strategy. Although simplified, the scenario for two intersections is still complex and the equation that determines the platoon split location x_L is bounded by certain conditions. The following paragraphs provide a discussion on the limitations of equation (12).

The first limitation involves the length of the queue at the downstream intersection (Q_L). If the traffic signal at this intersection is red, the earliest that it can turn green is at time t_0 (when the EV receives the call from dispatch). If the vehicle queue is longer than a certain length, the vehicles discharging from the upstream intersection and the EV will have to slow down prior to the downstream intersection (see Figure 3). The maximum length of the downstream queue (Q_L) to provide enough time for the EV to travel through the downstream intersection unimpeded is formulated as follows:

Equation (13) provides the time it takes for the first vehicle at the upstream intersection to reach the back of the downstream intersection queue. Assuming the upstream and downstream traffic signals turn green at time t_0 , the time the last vehicle in the downstream queue starts to move is found with the following equation:

$$t_6 = \frac{Q_L}{w} \quad (16)$$

Solving (13) and (16) simultaneously for Q_L , the maximum length that the downstream vehicle queue can be for the scenario equation to hold is as follows:

$$Q_{Lmax} = z \frac{u^{-1}}{w^{-1} + u^{-1}} \quad (17)$$

The second limitation is related to the location of the EV in the upstream intersection vehicle queue. If the location of the EV is close to the intersection, the solution equation (6) will provide a platoon split location that is downstream of the upstream intersection. This will allow the EV to change lanes before the critical location and catch the preceding vehicle prior to the downstream intersection (see Figure 3). To determine the minimum value for d , the value of x_L is set to zero in equation (12). Solving the equation for d produces the following equation:

$$d_{min} = z \frac{u^{-1} - v^{-1}}{w^{-1} + u^{-1}} \quad (18)$$

Emergency Vehicle Preemption Strategies

Traditional preemption strategies may not work well in an urban environment with closely spaced intersections where background traffic cannot move out of the EV's way. Depending on

the length of vehicle queues, discharging vehicles may enter the queue of the downstream intersections resulting in delay of the EV.

To address this issue, three EV preemption strategies were developed to provide an unimpeded path for the EV. They include a queue length determined preemption order strategy, a queue length sequential preemption order strategy, and an all-at-once strategy. A brief description of the strategies is provided in the following paragraphs with further explanation in the Methodology section.

Queue Length Based Preemption Order

This strategy uses shockwave theory to determine the order in which a group of signalized intersections should be preempted based on the vehicle queue length on the EV's approach leg. This allows for the vehicle queues at downstream intersections to be discharged prior to the arrival of the upstream vehicle platoon. After the EV passes each intersection, the traffic signal reverts back to normal operation.

The methodology for this strategy involves using shockwave theory to make estimates on how long it takes for vehicle queues to discharge. The queue discharge estimations are then used to determine the order of signal timing preemption to reduce the travel time of the EV and the impact to background traffic.

EV Arrival Time

The setting of this study is simplified and uses a roadway facility that does not include access points. It is assumed that the EV does not encounter any delays prior to the intersections. The arrival time of the EV can be made by dividing the distance the EV is from the last intersection by the EV's speed.

Signal Timing and Preemption Order

As a traffic light alternates between green and red phases it creates discontinuities or shock waves in the traffic stream. The LWR theory is particularly suitable to predict these shock waves since the boundary conditions are well-defined (e.g., the backward moving shock waves start at the stop bar when signal phase changes). Furthermore, the queue discharging process at

signalized intersections has been shown to be quite stable (25), which enables predicting the shock wave speed reliably.

Figure 3 shows a typical shock wave diagram for the formation and dissipation of a vehicle queues at adjacent traffic lights. The backward moving shock waves start at t_R (the beginning of the red phase) and t_0 (the time when the traffic signal turns green) and thus represent the back of the queue and front of the queue (or discharging process), respectively. The speed of the shock wave for the queue discharge, w , and the free-flow speeds (or desired speeds) of regular vehicles are assumed to be known.

To determine when a traffic signal should be preempted to clear potential vehicle queues at downstream intersections, the formulation developed by Jordan and Cetin (26) was used. Figure 3 shows the shock waves that define the boundaries of the queue and the trajectory of the first vehicle departing from the upstream intersection. The formulation for calculating this time is provided below and uses the following variables:

- w : the shock wave speed for the discharging flow at the signalized intersection
- u : desired speed for background vehicles
- z : the intersection spacing
- Q_L : the queue length of the downstream intersection
- t_G : the time when the preemption should occur

The time the first vehicle departing from the upstream intersection reaches the back of the queue at the downstream intersection can be found as,

$$t_1 = \frac{z - Q_L}{u} \quad (19)$$

The time it takes for the vehicle queue at the downstream intersection to discharge can be calculated with,

$$t_1 = t_G + \frac{Q_L}{w} \quad (20)$$

where t_G is the time the signal turns green.

Solving (1) and (2) simultaneously for t_G provides the following equation:

$$t_G = \frac{z - Q_L}{u} - \frac{Q_L}{w} \tag{21}$$

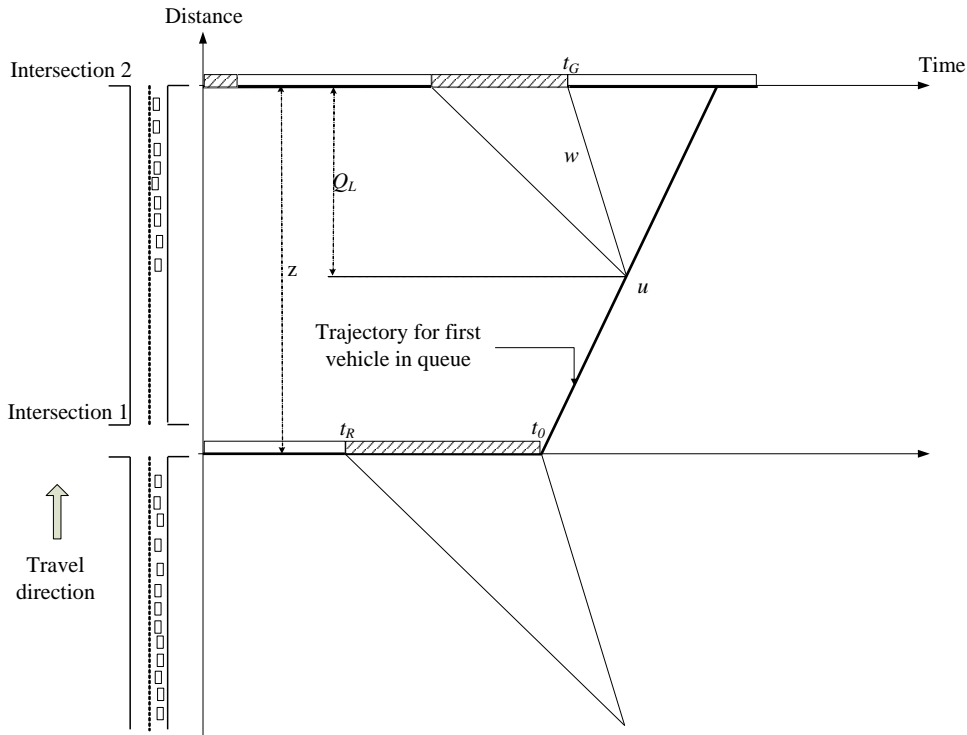


Figure 3: Typical shock wave diagram at adjacent intersections.

The signal timing preemption t_G is relative to the time when the upstream intersection turns green.

It should be noted that if the queue length of the downstream intersection is beyond a certain length, it will be necessary to preempt that signal prior to the upstream intersection. To determine this critical queue length the following equations were determined:

Equation (22) provides the time it takes for the first vehicle at the upstream intersection to reach the back of the downstream intersection queue. Assuming the upstream and downstream traffic signals turn green at time t_0 , the time the last vehicle in the downstream queue starts to move is found with the following equation:

$$t_1 = \frac{Q_L}{w} \quad (22)$$

Solving (1) and (4) simultaneously for Q_L provides the equation for determining the critical queue length:

$$Q_L = z \frac{u^{-1}}{w^{-1} + u^{-1}} \quad (23)$$

If the downstream intersection queue length is longer than Q_L in equation (23), the downstream intersection will need to be preempted prior to the upstream intersection in order for the queue to be discharged prior to the arrival of the upstream vehicle queue.

After the preemption signal timing and the critical queue length have been determined, the order of preemption must be determined based off of a reference intersection. The reference intersection is determined by applying the signal timing determined in equation (21) to the farthest downstream intersection as compared to its adjacent upstream intersection. The process is continued for each intersection in the upstream direction. The signal timing is then normalized around the reference intersection which is the signalized intersection with the earliest preemption.

To assist in the explanation of the signal timing and preemption order process, an example is provided below. The following values are used in this example:

$$w = 16 \text{ kph}$$

$$u = 50 \text{ kph}$$

$$z = 80 \text{ kph}$$

$$Q_L = \text{the values identified in Table 1}$$

Table 1: Traffic Signal Preemption Timing

	Intersections				
	1	2	3	4	5
Q_L	70	70	120	70	70
t_G	2.9	-11.9	2.9	2.9	0
t_G (referenced to adjacent)	-3.2	-6.1	5.8	2.9	0
t_G (normalize)	9.0	11.9	0*	2.9	5.8

Note: The (*) identifies the reference intersection.

The values for t_G are determined using equation (21). This value indicates when the intersections traffic signal should be preempted in comparison to its adjacent upstream intersection. The farthest downstream intersection (intersection 5) is used as a dummy reference intersection and the signal timing is set to zero. Intersection 4 signal timing is determined by adding its t_G value with intersection 5's signal timing. This gives a value of 2.9. Intersection 3 signal timing is determined by adding its t_G value with intersection 4 signal timing. This gives a value of 5.8 (2.9 + 2.9). This process is continued upstream for the remaining intersections.

After the signal timings have been determined the traffic signal with the earlier signal timing is chosen as the reference intersection. In the example, it is intersection 3. The signal timings are then normalized by taking the difference between the reference timing and each intersection. For example, the difference between the reference intersection and intersection 2 is 11.9 seconds therefore the timing for intersection 2 is 11.9. The difference between the reference intersection and intersection 1 is 9.0 seconds therefore the timing for intersection 2 is 9.0.

As identified in Table 1, the reference intersection is intersection 3. The signal timings are based off this intersection and result in the preemption order of intersection 3, 4, 5, 1, 2. The calculated signal timing and preemption order will provide sufficient time for the vehicle queue to discharge prior to the arrival of the EV.

The time when the reference traffic signal needs to be preempted in order to provide unimpeded travel for the EV is determined based on the EV's distance away from the last traffic signal along the corridor. The distance must be far enough away to provide enough time for the last vehicle in the vehicle queue at the first intersection to travel past the last intersection. This distance is determined by the following formula and is illustrated in Figure 4:

$$d = v * \left(\frac{Q_L}{w} + \frac{Q_L}{u} + \sum_{i=1}^{n-1} \frac{z_i}{u} \right) \quad (24)$$

Where

n : the number of intersections

z_i : spacing between adjacent intersections

Q_L : the queue length of the first intersection

Equation (24) is derived by summing the time it takes for the last vehicle at the first intersection to reach the last intersection.

Continuing with the example identified in Table 1, the EV's distance to the last intersection needs to be 2,574 meters upstream in order for the queues to discharge for an unimpeded path for the EV.

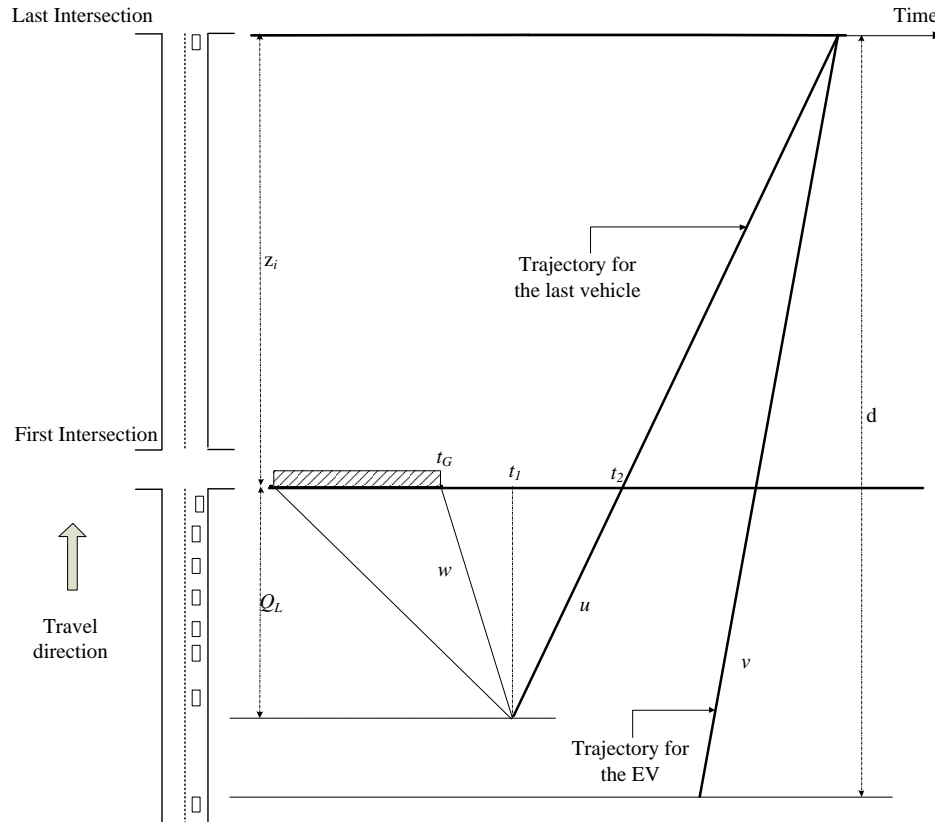


Figure 4: Shock wave diagram for signal preemption timing.

Sequential Preemption Based on Queue Lengths

This strategy is similar to the queue length determined preemption order. Rather than the order of the traffic signals being determined by the queue length, they are preempted sequentially. The preemption timing is determined by the queue length at the signalized intersection.

The methodology for this strategy involves using shockwave theory to make estimates on how long it takes for vehicle queues to discharge. The queue discharge estimations are then used to determine the timing of the preemption. The signals are preempted in sequential order.

EV Arrival Time

It is assumed that the EV does not encounter any delays prior to the intersections because of the simplified roadway network. The arrival time of the EV is determined the same way as the previous strategy but to the first intersection rather than the last.

Signal Timing

To determine when a traffic signal should be preempted, equation (24) is used. The intersections are evaluated individually in this strategy and therefore, the value of $z = 0$. The time when the first intersection traffic signal needs to be preempted is determined based on the EV's distance away from the intersection.

All-At-Once

Another method to provide a path for the EV is preempting a series of closely spaced traffic signals all at once. This would allow all vehicles at each intersection to discharge at the same time and travel down the corridor leaving an empty roadway for the EV to travel.

The all-at-once strategy involves all traffic signals in a group to be preempted at the same time to provide green lights along the EV's route. After the EV passes the intersection, the traffic signal reverts back to normal operation.

EV Arrival Time

The setting of this study is simplified and uses a roadway facility that does not include access points. It is assumed that the EV does not encounter any delays prior to the intersections. The arrival time of the EV can be made by dividing the distance the EV is from the last intersection by the EV's speed.

Signal Timing

The signal timing preemption is determined using the same methodology in the Queue Length Determined Preemption Order Strategy (equation 22). The signals are preempted when the emergency vehicle is a certain distance from the last intersection but all the intersections are preempted at the same time.

SIMULATION

PTV's VISSIM[®], microscopic traffic simulation package, was used to evaluate the formulated algorithms. VISSIM applies discrete time and agent based simulation to model traffic operations. Each vehicle is simulated as a separate object with a specific set of car-following and lane-changing behaviors. The program tracks specific attributes such as speed, location, and vehicle type for every vehicle at each time step. The unique driving characteristics and flexibility of the software allows complex transportation roadway networks to be developed.

VISSIM provides users the ability to control certain functions and attributes of the microscopic simulation with outside programs during the simulation runs using the COM (component object model) interface. This allowed for information to be passed between the programs and for implementing the study algorithms. The COM was used to track the location of vehicles, calculate x_L , instruct vehicles to stop upstream of x_L , initiate lane changing of the EV, and change the signal phases.

Platoon Split Strategy

The roadway network used in the simulation consisted of a straight two-lane roadway approximately 2 kilometers in length with two intersections and no other obstructions. Traffic was loaded at a rate of 800 vehicles per hour per lane to create traffic congestion at the signalized intersections. The traffic composition consisted of passenger cars only to provide similar driving behaviors. Simulation runs were performed with a set of random seeds and EVs were added to the network at different random times to produce varying traffic congestion and vehicle queues at the intersections.

Simulation Scenarios

To determine if the developed strategies would work in a simulated environment, six scenarios were run for comparison and are listed below.

- One Intersection
 - Only signal preemption (EV in vehicle queue without equipment to alert drivers of its presence)
 - Platoon split strategy with preemption

- Two Intersections
 - Only signal preemption
 - EV with siren (EV in vehicle queue with a siren to alert drivers of its presence)
 - EV with siren and preemption (EV in vehicle queue with a siren and traffic signal equipped with preemption)
 - Platoon split strategy with preemption

The platoon split simulation runs were performed for each of the following vehicle speeds. The speeds reflect a sample of speeds that can be found in an urban environment.

- Speed Setting 1: Non-EV 50 kph and EV 80 kph
- Speed Setting 2: Non-EV 50 kph and EV 65 kph
- Speed Setting 3: Non-EV 72 kph and EV 86 kph

Due to time constraints, the EV with siren and EV with siren and preemption simulation runs were performed with speed setting 1 only. In addition, the two intersection scenarios included the evaluation of three intersection spacing values (1000 m, 500 m, and 250 m).

Signal Preemption Strategy

The roadway network used in the simulation consisted of a straight one-lane roadway approximately 3 kilometers in length with five intersections and no other obstructions. An initial traffic state was used that included vehicle queues at each of the five intersections. Traffic was loaded at a rate of 1,000 vehicles per hour on the major roadway and 400 vehicles per hour on the minor roadways. The traffic composition consisted of passenger cars only to provide similar driving behaviors. Simulation runs were performed with a set of random seeds.

The scenarios were simulated with the following vehicle and shockwave speeds. The vehicle speed reflects speeds that can be found in an urban environment.

- Non-EV: 50 kph
- EV: 80 kph
- Shockwave: 16 kph

Assumptions/Limitations

The following is a list of assumptions that were used in the simulation runs:

1. The roadway network is equipped with V2I systems.
2. All vehicles are equipped with V2V/V2I systems and comply with the given instructions.
3. The information exchanged between vehicles and the infrastructure has a range of 300 meters and occurs without delay or failure.
4. There is adequate storage downstream of the last intersection to accommodate vehicles.
5. All non-emergency vehicles have the same desired speed.
6. Non-emergency vehicles can only change lanes when emergency vehicles approached from behind.

RESULTS

This section provides the results of the simulation runs for the strategies identified in the previous sections.

Platoon Split Strategy

This subsection provides the results of the simulation runs for the platoon split strategy. Analyses were performed to compare the travel time from each simulation run to the base conditions.

Theoretical Results

The theoretical travel time improvements for the one intersection scenario can be determined from Figure 1 by comparing the arrival time of the EV with and without the use of the platoon split strategy (time t_4 and time t_5 , respectively). The dotted line in Figure 1 from location x_L to time t_5 illustrates the EV trajectory without the implementation of the platoon split strategy. The formulation of the travel time savings percentage is provided below with t_s as the percent time savings.

$$t_s = \frac{t_5 - t_4}{t_5 - t_2} \quad (25)$$

Time t_5 can be determined from Figure 1 with the following equation:

$$t_5 = \frac{d}{w} + \frac{d}{u} \quad (26)$$

By substituting equations (2), (5), and (25) into equation (26), the following equation is determined:

$$t_s = \left(\frac{x_L}{d}\right) \left(\frac{u^{-1} - v^{-1}}{u^{-1}}\right) \quad (27)$$

From equation (6) the following relationship is formulated:

$$t_s = \left(\frac{w^{-1} + u^{-1}}{w^{-1} + 2u^{-1} - v^{-1}} \right) \left(\frac{u^{-1} - v^{-1}}{u^{-1}} \right) \quad (28)$$

Equation (28) can be used to determine the theoretical time savings for the platoon split strategy with knowledge of varying desired speeds for the EV and background traffic and for the shock wave speed.

The theoretical maximum time savings for the two intersection scenario can be determined in a similar manner from Figure 2 by comparing the arrival time of the EV with and without the use of the platoon split strategy (time t_4 and time t_5 , respectively). The formulation of the travel time savings percentage results in the same relationship. Therefore, the theoretical travel time savings are identical for the one intersection and two intersection scenarios.

The following table provides the theoretical time savings percentage for the tested speeds for the one intersection and two intersection scenarios. As shown in Table 2, the percent time savings increase as the difference between u and v gets larger.

Table 2: Theoretical Time Savings

Speed Setting	Background Traffic Speed	EV Speed	Shock Wave Speed	Travel Time Savings
	u	v	w	Percent
1	50	80	19	34%
2	50	65	19	22%
3	76	86	19	16%

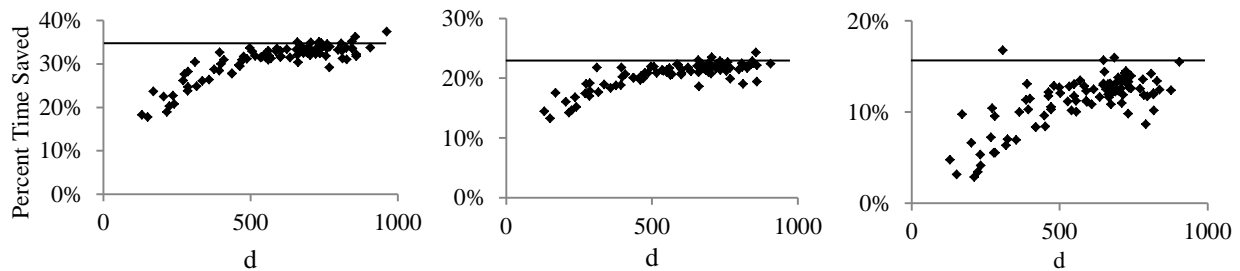
Note: Speeds are in kph.

Simulation Results

After each simulation run, the time when vehicles passed certain locations were recorded. In particular, the time instant when the EV joined the back of the queue (time t_0), the time at which the EV departed from the queue (time t_2), the time at which the EV changed lanes (time t_3), and the time at which the EV entered the upstream intersection (time t_4) were recorded. Simulation

runs were completed for both with and without the implementation of the strategy presented to compare the EV travel times and determine the time savings.

Figure 5 summarizes the results for each simulation run for the three speed settings for the one intersection scenario. It shows the percent reduction in travel time for the EV versus the distance d . The data indicates that the time savings ranges from 3% to 35% (1 second to 21 seconds) and varies depending on the distance from the upstream intersection (d). It was noticed that as d increases beyond 500 meters, the increase in percentage savings begins to level off near the theoretical limit (the horizontal black line).



Notes: Each of the three graphs represent different speed settings (from left to right represent speed settings 1, 2, and 3). The straight black lines identify the theoretical travel time savings (34%, 22%, and 16% for speed settings 1, 2, and 3, respectively).

Figure 5: Percent improvement in EV travel time for one intersection at varying speed settings.

Theoretically, the percent reduction in travel times should not change as d varies. Based on the desired speeds used in the simulation, the theoretical percent reduction in travel times should be around 34% for speed setting 1, around 22% for speed setting 2, and 16% for speed setting 3. However, the LWR formulation does not account for driver reaction time, acceleration and deceleration behavior, and assumes that vehicles can change speed instantaneously. When the distance d is short, the driver reaction time and the acceleration and deceleration impact the travel times more substantially. However, as d increases the impacts of these factors become negligible.

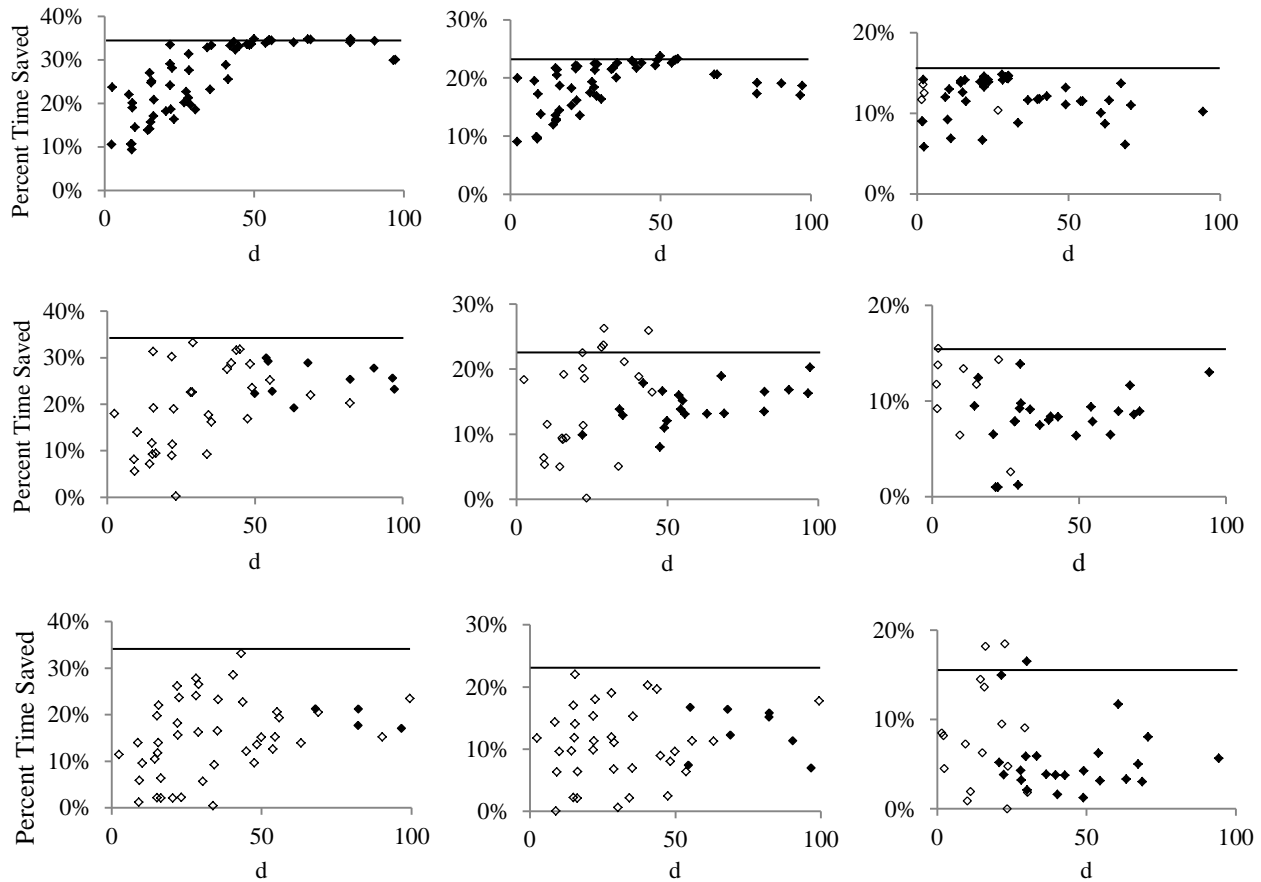
Figure 6 summarizes the results for the simulation runs for the two intersection scenario with each of the three speed settings and the three intersection spacing values. It shows the percent reduction in travel time versus the distance d . The solid data points indicate the downstream

intersection queue length during the simulation run was less than the maximum queue length limitation (Q_{Lmax}). The hollow data points indicate the downstream intersection queue length was greater than Q_{Lmax} .

The data for intersection spacing of 1000 m indicates that the time savings varies between 6% and 34% (4 seconds and 26 seconds) depending on the distance from the upstream intersection (d) and the downstream queue length. It was noticed that as d increases beyond 50 meters, the increase in percentage savings begins to level off near the theoretical limit. The distance d , where travel time savings approaches the theoretical value, is significantly smaller (closer to the intersection) than in the one intersection scenario. This is due to the distance that the EV can travel at its desired speed, which is much longer for the two intersection scenario.

The data for intersection spacing of 500 m indicates that the time savings varies between 0% and 33% (0 seconds and 20 seconds). The shape of the data points is similar to the 1000 m spacing data points but the variability in the percent time saved is larger. This is because of the large number of simulation runs that had downstream queues larger than Q_{Lmax} .

The data for intersection spacing of 250 m indicates that the time savings varies between 0% and 33% (0 seconds and 11 seconds). The shape of the data points is similar to the 500 m spacing points but as d increases beyond 50 m the travel time savings does not approach the theoretical limit. This can be attributed to the downstream queue lengths being the same lengths for each set of simulation runs. Each simulation run for the 1000 m, 500 m, and 250 m intersection spacing scenario were run with the same random seed set and had identical traffic patterns. The intersection spacing determines the maximum length the downstream queue can be to provide an unimpeded path for the EV. Therefore, the number of simulation runs that have downstream queue lengths greater than Q_{Lmax} increases when the intersection spacing decreases. If the length of the downstream queue is longer than Q_{Lmax} , the EV will have to slow down prior to the downstream intersection reducing the time savings percentage.



Notes: Each row represents different intersection spacing (Rows 1, 2, and 3 represent 1000m, 500m, and 250m intersection spacing, respectively). Each column of graphs represent different speed settings (Columns 1, 2, and 3 represent speed settings 1, 2, and 3, respectively). The straight black lines identify the theoretical travel time savings (34%, 22%, and 16% for speed settings 1, 2, and 3, respectively).

Figure 6: Percent improvement in EV travel time at varying intersection spacing and varying speed settings.

Table 3 provides the results of a statistical analysis comparing the EV with siren and EV with siren and preemption simulation runs with the platoon split strategy simulation runs. The comparison includes the speed setting 1 (50 kph background traffic, 80 kph EV) with the two intersection scenario. The time needed to run the EV with siren and EV with siren and preemption simulations was large; therefore, only the speed setting 1 with the 1000 m intersection spacing scenario was performed. The table is organized as follows: The first column indicates the simulation run comparison. The second and third columns indicate the average EV travel time difference and the standard deviation of the EV travel time difference between the comparisons identified in the first column. The fourth column provides the z value for the 95% confidence interval, and column five gives the sample size. The last two columns provide the lower and upper bounds for the 95% confidence interval.

Table 3: Confidence Intervals for Average EV Travel Time Difference

Comparison	Average Travel Time Difference	Standard Deviation of Travel Time Difference	z value	Sample Size	95% Confidence Interval	
	\bar{D}	σ_d	$z_{0.25}$	n	Lower	Upper
EV with Siren vs EV with Siren and Preemption	8.01	6.48	1.96	30	5.69	10.33
EV with Siren vs Platoon Split	25.36	8.91	1.96	30	22.17	28.55
EV with Siren and Preemption vs Platoon Split	11.36	5.96	1.96	30	9.23	13.49

The estimate, with 95% confidence, indicates that the difference between the EV travel times with the platoon split falls within the intervals in the last two columns of Table 3 (Lower, Upper). Since the value 0 is not within the intervals for any of the three comparisons, there is sufficient evidence to conclude that there is a difference between the EV travel times with the implementation of the platoon split strategy and the EV with siren and EV with siren and preemption simulation runs.

Market Penetration Effectiveness

The microscopic simulation runs were performed assuming the market penetration of V2V equipped vehicles was at 100%. This will likely not occur in the foreseeable future. To evaluate the benefits of the proposed strategy at different market penetration rates, a probabilistic analysis was performed. An equation was derived for the expected travel time savings for different market penetration rates and is provided below. The expected value of the travel time saving is represented by $E(TTS)$. The formulation for the equation has been omitted due to space limitation but will be further explored in subsequent studies. The following variables were used in the formulation:

TT : theoretical travel time savings (identified in Table 1)

n : the number of vehicles in the queue between the intersection and the critical split point (x_L)

p : market penetration value of V2V equipped vehicles

$$E(TTS) = TT \left[\left(\frac{n+1}{n} \right) + \left(\frac{(1-p)^{n+1} - 1}{np} \right) \right] \tag{29}$$

A graph is provided in Figure 7 that identifies the expected travel time savings for different market penetration rates for each of the three speed settings (identified in Table 1). As can be observed in the graph, market penetration rates greater than 20% are expected to provide travel time savings greater than 60% of the theoretical limit.

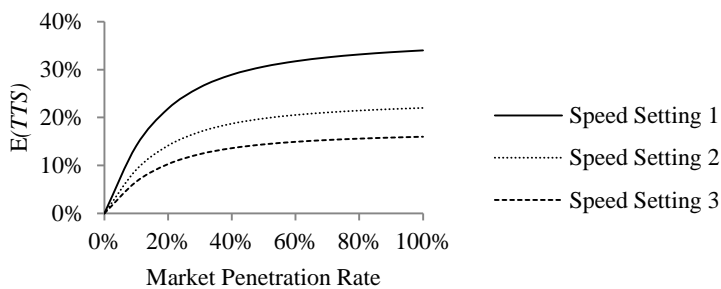


Figure 7: Percent travel time savings for different market penetration rates.

Signal Preemption Strategy

After each simulation run, the travel time of the EV and the background vehicles were recorded. Simulation runs were completed for each strategy presented to compare the results between strategies. The following sections describe the results.

EV Travel Time

The EV travel time was recorded for each simulation run. The simulation runs were performed for each of the three preemption strategies.

The following are the average EV travel times from the distance *d* to the last intersection for the simulation runs:

- All-at-once: 133.4 seconds
- Queue Length Determined Preemption Order: 130.5 seconds
- Queue Length Sequential Preemption Order: 221.0 seconds

The all-at-once strategy was arbitrarily chosen as the base condition for which the other strategies are compared. Table 4 summarizes the results for the simulation runs. The table is organized as follows: The first column indicates the simulation run comparison. The second and third columns indicate the average EV travel time difference and the standard deviation of the EV travel time difference between the comparisons identified in the first column. The fourth column provides the z value for the 95% confidence interval, and column five gives the sample size. The last two columns provide the lower and upper bounds for the 95% confidence interval.

Table 4: Confidence Intervals for Average EV Travel Time Difference

Comparison	Average Travel Time Difference	Standard Deviation of Travel Time Difference	z value	Sample Size	95% Confidence Interval	
	\bar{D}	σ_d	$z_{0.25}$	n	Lower	Upper
Queue Length Determined Preemption Order vs All-at-once	1.85	1.59	1.96	30	1.28	2.42
Queue Length Sequential Preemption Order vs All-at-once	88.63	1.26	1.96	30	88.18	89.08

The estimate, with 95% confidence, indicates that the difference between the EV travel times with the all-at-once strategy falls within the intervals in the last two columns of Table 4 (Lower, Upper). Since the value 0 is not within the intervals for any of the three comparisons, there is sufficient evidence to conclude that there is a difference between the EV travel times of the queue length determine preemption and the all-at-one strategy. Additionally, there is sufficient evidence to conclude that there is a difference between the EV travel time of the queue length sequential preemption order and the all-at-once strategy.

The average travel time difference between the queue length sequential preemption order and the other strategies was so large that further evaluation of the strategy was not performed.

Background Traffic Delay

The total delay for background traffic was recorded for each simulation run. The simulation runs were performed for the All-at-once (Scenario 1) and the Queue Length Determined Preemption Order (Scenario 2).

Table 5 summarizes the results for the simulation runs. The table is organized as follows: The first column indicates the scenario. Columns 2 through 6 indicate the intersection number with each column having two sub columns which identify the two minor approaches. The values in the table are in seconds and identify the average delay incurred during the signal preemption and for two cycles after the preemption for the simulation runs.

Table 5: Average Background Traffic Delay for Minor Approaches

Minor Approach	Intersections									
	1		2		3		4		5	
	1	2	1	2	1	2	1	2	1	2
Average Delay Scenario 1	54.0	55.6	53.4	54.3	52.5	48.6	66.3	60.1	84.2	84.3
Average Delay Scenario 2	36.0	38.2	32.4	32.9	53.5	49.8	61.9	56.2	67.7	68.4
Difference in Average Delay	17.9	17.4	21.0	21.4	-1.0	-1.2	4.4	3.9	16.5	15.8

Notes: The delay values are in seconds.
 Scenario 1: All-at-once strategy
 Scenario 2: Queue Length Determined

The average delay for the all-at-once strategy is significantly higher than the queue length determine preemption order strategy for the minor approaches for intersections 5, 1, and 2. The average delays on the minor approaches for intersection 4 were slightly higher than the Queue Length Determined Preemption Order strategy. The minor approaches for intersection 3 were slightly lower than the queue length Queue Length Determined Preemption Order strategy. This is consistent with the signal timing order and signal timings identified in Table 1.

CONCLUSIONS

This study evaluated new strategies to enable emergency response vehicles to traverse congested roadways and through congested intersections more quickly, an improvement that may be critical to patient's survival rates. The first strategy focused on EVs already in vehicle queues at signalized intersection while the other was focused on EVs prior to the arrival at congested intersections.

The application of the platoon split concept was illustrated for two scenarios. The scenarios investigated splitting the vehicle queue on one lane at a critical location so that an EV could proceed at its desired speed while the disruption to background traffic was minimized. The formulations were developed based on the shock wave theory of traffic flow to predict the queuing behavior at signalized intersections. The proposed method was simulated in VISSIM for evaluation.

The results indicated that this strategy can shorten the trip times significantly for EVs for the one intersection and two intersection scenarios. The simulation results showed time saving percentages approached the theoretical maximum values (ranging from 16% to 34% depending on the relative speeds of the EV and other vehicles) as d is increased at 100% market penetration rate. Considerable travel time savings are expected when market penetration rates are as low as 20%.

The application of the signal preemption concept was illustrated for three scenarios. The scenarios investigated preempting the traffic signals all-at-once, sequentially, and determined by queue length. The formulations were developed based on the shock wave theory of traffic flow to predict the queuing behavior at signalized intersections. The proposed methods were simulated in VISSIM for evaluation.

The results indicated that queue length determined preemption order can shorten the trip times for EVs over the other proposed strategies. The simulation results showed EV travel time savings of approximately 2 seconds over the all-at-once strategy and 88 seconds over the sequential strategy. In addition, the delay incurred by background traffic is significantly lower for the queue length determined preemption order strategy than the all-at-once strategy.

Future work will expand on this research by relaxing the controlled environment. In particular, simulation runs will be performed with vehicle speeds being randomly distributed over a larger range of values. The V2V communication system will be coded in a network simulator to more accurately simulate message propagation and include signal degradation. Driver compliance rates will be included in the simulation runs to evaluate their effect on time savings. In addition, different types of vehicles other than passenger vehicles (i.e. trucks, motorcycles, buses) will be included in the simulations. The simulation roadway network will also be expanded to include left turning vehicles and access points between signalized intersections. Additionally, simulation runs will be performed on larger networks with more intersections and with roadways that have more lanes.

The use of the proposed strategies will impact the overall traffic performance and some background vehicles will have an increase in delay. The implementation of the strategy may be dependent on the level of urgency of the emergency. The impacts of the proposed strategy will be evaluated and trade-offs will be explored in providing preference to EVs.

ACKNOWLEDGEMENTS

This study was funded in part by the TranLIVE University Transportation Center (UTC), a consortium of five universities, funded by the US DOT's Research and Innovative Technology Administration (RITA).

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APPENDIX

Publications resulting from this project:

Jordan, C. A., M. Cetin, and R. M. Robinson. Path Clearance for Emergency Vehicles Through the Use of Vehicle-to-Vehicle Communication. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2381, No. 1, 2013, pp. 45-53.

Jordan, C. and M. Cetin, "Signal Preemption Strategy for Emergency Vehicles Using Vehicle to Infrastructure Communication," To be presented at the 94th Annual meeting of the TRB, Washington, D.C. January 11-15, 2015, paper # 15-5723.